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## RESEARCH ARTICLE

10.1002/2013TC003388

## Key Points:

- Paleomagnetic study reveals Oligocene clockwise rotation along eastern Pamir
- Until Miocene Pamir developed symmetrically by radial thrusting
- From Miocene asymmetric deformation with transfer faulting along eastern Pamir

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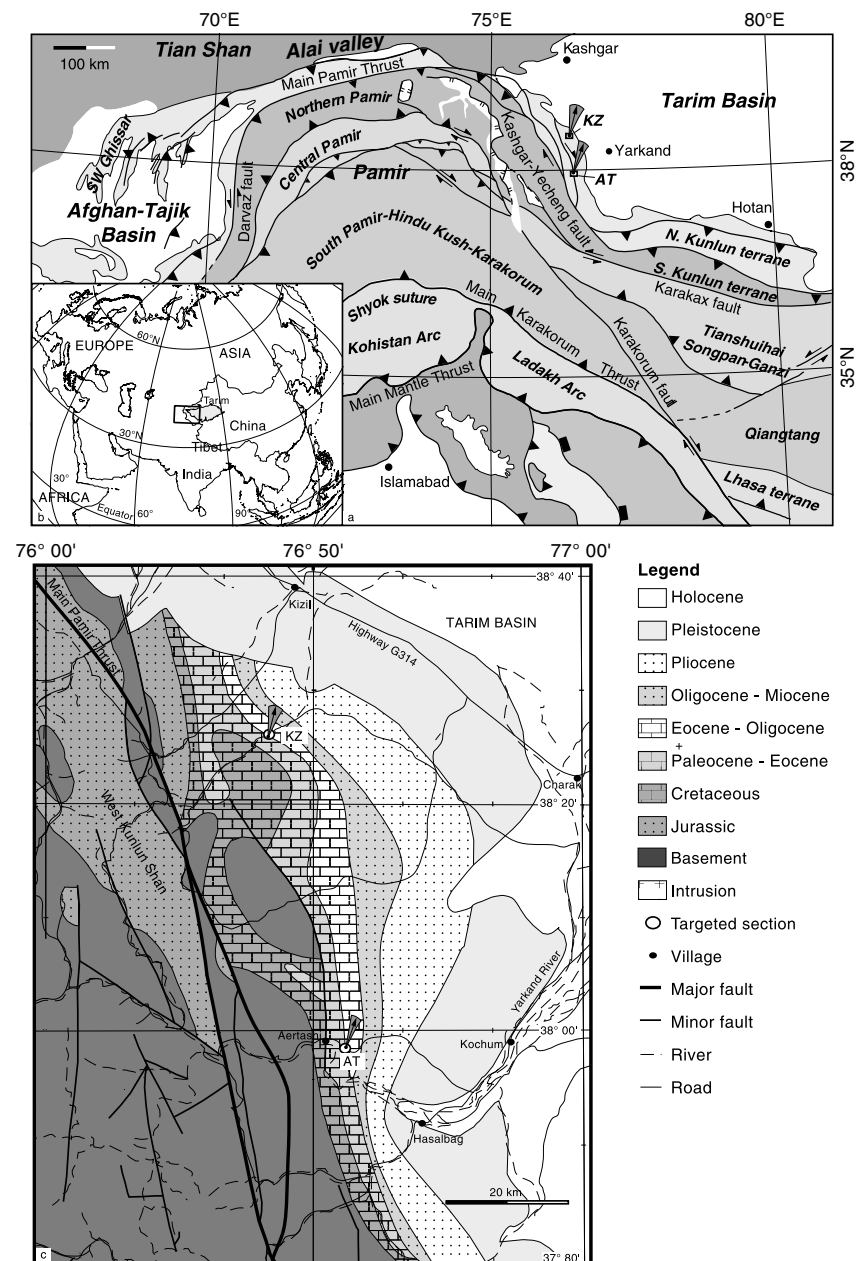
# Oligocene clockwise rotations along the eastern Pamir: Tectonic and paleogeographic implications

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**Abstract** Despite the importance of the Pamir range in controlling Asian paleoenvironments and land-sea paleogeography, its tectonic evolution remains poorly constrained in time and space, hindering its potential for understanding deep to surface processes. We provide here new constraints on vertical-axis tectonic rotations from the southwest Tarim Basin along the eastern flank of the Pamir arcuate range based on paleomagnetic results. Two well-dated Eocene to Oligocene sections, previously analyzed using biostratigraphy and magnetostratigraphy, yield consistently clockwise rotations of  $21.6 \pm 4.2^\circ$  in 41 to 36 Ma strata then  $17.1 \pm 6.5^\circ$  in 33 to 28 Ma strata at the Aertashi section and  $14.2 \pm 11.5^\circ$  in 41 to 40 Ma strata at the Kezi section. Combined with a regional review of existing paleomagnetic studies, these results indicate that most of the clockwise rotations along the eastern Pamir occurred during Oligocene times and did not extend systematically and regionally into the Tarim Basin. In contrast, on the western flank of the Pamir tectonic rotations in Cretaceous to Neogene strata are regionally extensive and systematically counterclockwise throughout the Afghan-Tajik Basin. This timing and pattern of rotations is consistent with paleogeographic reconstructions of the regional sea retreat out of Central Asia and supports a two-stage kinematic model: (1) symmetric rotations of either flanks of the Pamir arcuate range until Oligocene times followed by (2) continued rotations on its western flank associated with radial thrusting and, along the eastern flank, no further rotations due to decoupled transfer slip starting in the Early Miocene.

## 1. Introduction

The arcuate Pamir range (Figure 1) formed during the northward indentation of India into Asia, constituting a prominent tectonic feature and a major paleogeographical divide with important implications on Asian paleoclimate evolution [Bershaw *et al.*, 2012; Burtman and Molnar, 1993]. It closed the Tarim Basin to the east from the Afghan-Tajik and Ferghana Basins to the west and partly forced the retreat of an epicontinental sea that formerly extended across Eurasia [Bosboom *et al.*, 2014; Bosboom *et al.*, 2011; Bosboom, 2013]. Lithospheric structures below the Pamir inferred from teleseismic and tomographic studies [Negredo *et al.*, 2007; Sippl *et al.*, 2013] suggest a complex history of slab break off, continental subduction inversion, and roll back [e.g., Sobel *et al.*, 2013]. Despite the importance of this range and its potential for understanding deep to surface processes, its tectonic evolution remains poorly constrained in time and space. The general consensus is that the Pamir indented northward ~300 km into the Eurasian continent [e.g., Burtman and Molnar, 1993; Cowgill, 2010], starting in Early Eocene times as a relatively straight east-west range aligned with the West Kunlun Shan and ending as the highly curved concave southward range observed today. The acquisition of this peculiar geometry has been proposed to be related either to oroclinal bending or radial thrusting associated with regionally extensive vertical-axis rotations [Bazhenov and Burtman, 1986; Bazhenov *et al.*, 1994; Robinson *et al.*, 2004; Strecker *et al.*, 1995] or to transfer faulting induced by opposite shear along the eastern (sinistral) and western (dextral) margins of the Pamir with limited to no vertical-axis rotations [Burtman and Molnar, 1993; Searle, 1996]. Paleomagnetism provides an opportunity to differentiate between these proposed kinematic models by its ability to quantify and date vertical-axis rotations of crustal fragments with respect to a stable continent [Butler, 1992]. Paleomagnetic studies in the Afghan-Tajik Basin on the west side of the Pamir have revealed regionally consistent counterclockwise vertical-axis rotations [Bazhenov and Mikolaichuk, 2002; Bazhenov *et al.*, 1994; Burtman, 2000; Pozzi and Feinberg, 1991; Thomas *et al.*, 1993, 1994]. However, along its eastern flank in the Tarim Basin, West Kunlun Shan, Altyn Tagh, and Tian Shan various rotation studies show large discrepancies in both sense and magnitude of rotation [e.g., Chen *et al.*, 1992; Gilder *et al.*, 1996; Li *et al.*, 2013;



**Figure 1.** Simplified tectonic map of the Pamir collision zone (modified from Cowgill [2010]) showing the calculated rotations and their uncertainties with respect to the Eurasian apparent polar wander path (APWP) at the studied sections of Aertashi (AT) and Kezi (KZ) along the (a) eastern Pamir. (b) The inset shows the regional location of the Tarim Basin (present-day coastal outline obtained from GPlates 0.9.7.1). (c) The detailed geological map of the field area shows the lithostratigraphic units, tectonic features, and locations of the Aertashi (AT) and Kezi (KZ) sections along the eastern margin of the Pamir (modified from the 1:500,000 scale map of the Bureau of Geology and Mineral Resources of Xinjiang Uygur Autonomous Region [1993]).

Rumelhart *et al.*, 1999; Wei *et al.*, 2013; Yin *et al.*, 2000], hindering understanding of the kinematics underlying the tectonic evolution of the Pamir.

Here we provide new constraints on the vertical-axis tectonic rotation along the eastern flank of the Pamir (Figure 1), based on paleomagnetic results from two well-dated Eocene to Oligocene sections previously analyzed using bio- and magnetostratigraphy [Bosboom *et al.*, 2013]. We combine our results with a regional review of existing paleomagnetic results to constrain the timing, the sense, the magnitude, and the regional distribution of tectonic deformation and ultimately evaluate the tectonic and paleogeographic evolution of the Pamir.

## 2. Geological Setting

The Tarim Basin is a relatively undeformed crustal block within the Indo-Asia collision system [Yin and Harrison, 2000]. Thrusting and exhumation around the Pamir range is expressed by the Main Pamir Thrust bounding the Alai Valley to the north, the dextral Kashgar-Yecheng transfer system (KYTS) bounding the Tarim Basin on the eastern flank, and the sinistral Darvaz-Karakul strike-slip fault bounding the Afghan-Tajik Basin on the western flank (Figure 1). According to sedimentologic [Burtman, 2000; Yin *et al.*, 2002], stable isotope and provenance [Bershaw *et al.*, 2012], thermochronologic [Amidon and Hynek, 2010; Sobel and Dumitru, 1997], paleomagnetic [Thomas *et al.*, 1994; Yin *et al.*, 2002], and backstripping [Yang and Liu, 2002] data, these bounding structures are generally thought to have been active mostly into Miocene times with sparse evidence for earlier Eocene initiation.

The sedimentary infill on top of the crustal basement is primarily composed of Paleozoic and Mesozoic clastic sediments, recording the successive distal accretion of continental terranes along the southern margin of Asia from the Late Triassic until the Eocene Indo-Asia collision at ~50 Ma [Hendrix *et al.*, 1992; Jia *et al.*, 2004; Robinson *et al.*, 2003; Tian *et al.*, 1989; van Hinsbergen *et al.*, 2012; Yin and Harrison, 2000]. Distal marginal overthrusting and tectonic loading of the paleo-Tian Shan in the north and the paleo-Pamir-Kunlun orogenic system in the south by the Cenozoic northward movement of India into Eurasia probably initiated two major distal foreland basins, the Kuche depression along the southern margin of the Tian Shan and the southwest depression along the eastern Pamir with its depocenter near Yarkand (Figure 1) [Burtman and Molnar, 1993; Cowgill, 2010; Jia *et al.*, 1997; Yang and Liu, 2002; Yin and Harrison, 2000]. The progressive and long-term retreat of a shallow sea covering most of the Tarim Basin in the Early Eocene [Burtman, 2000; Burtman *et al.*, 1996; Lan and Wei, 1995; Tang *et al.*, 1989] has been related to distal tectonic deformation [e.g., Bosboom *et al.*, 2013; Wei *et al.*, 2013]. The sea retreated out of the paleodepocenter in the southwest depression in the middle Eocene [Bosboom *et al.*, 2011; Bosboom *et al.*, 2013] and out of the westernmost Tarim Basin in the Late Eocene [Bosboom, 2013]. Thereafter, continental deposition was predominant with relatively distal environments and remnant brackish-marine conditions up into the Oligocene [Ye *et al.*, 1996; Gao *et al.*, 2000; Graham *et al.*, 2005; Jia *et al.*, 2004; Kent-Corson *et al.*, 2009; Ritts *et al.*, 2008; Zheng *et al.*, 1999], followed by the Early Miocene initiation of rapid accumulation of coarse-grained clastics in proximal alluvial environments throughout the region [e.g., Bershaw *et al.*, 2012; Charreau *et al.*, 2005; Heermance *et al.*, 2007; Huang *et al.*, 2006; Jia *et al.*, 2004; Sobel and Dumitru, 1997; Sobel *et al.*, 2006; Thomas *et al.*, 1993, 1994].

The studied sedimentary sections are located along the eastern Pamir (Figure 1) within the western margin of the Tarim Basin, separated from the Pamir by the dextral Kashgar-Yecheng transfer system (KYTS) [Cowgill, 2010; Sobel *et al.*, 2011]. According to local structural work of Yin *et al.* [2002], the structural style of the studied area is apparently dominated by recent thrusting and dextral slip associated to the Kashgar-Yecheng transfer system (KYTS) and younger deformation.

## 3. Paleomagnetic Analyses

In order to quantify vertical-axis rotations, we present here the directional analysis of magnetostratigraphic results previously acquired from marine and continental sediments in the southwest Tarim Basin at the Aertashi (37°58'N, 76°33'E) and Kezi (38°26'N, 76°24'E) sections (Figure 1) [Bosboom *et al.*, 2013]. Bosboom *et al.* [2013] showed using rock and thermomagnetic analyses that the marine sediments of the Kashi Group at both sections all yielded normal polarity in the present-day field direction before bedding correction. This led Bosboom *et al.* [2013] to conclude that marine strata have been fully remagnetized and are unreliable for any paleomagnetic analyses. These marine sediments are thus unsuitable to infer vertical-axis rotations, although they have been included in some previous studies [e.g., Chen *et al.*, 1992; Huang *et al.*, 2009; Rumelhart, 2000; Li *et al.*, 2013]. In contrast, the overlying continental sequence of the Wuqia Group yielded remanent magnetizations of primary origin allowing reliable correlation to the geological timescale [Gradstein *et al.*, 2012]. The sampled interval within the Kezilouyi Formation (Figure 2) was constrained in age from the base of C18r to C9n (~41–27 Ma) [Bosboom *et al.*, 2013]. A ~3.5 Myr hiatus including the Eocene-Oligocene transition separates the Aertashi section into a lower part (base C18r–C16n.2n; ~41–36 Ma) and an upper part (base C12r–C9n; ~33–27 Ma). At the Kezi section only the very base of the Kezilouyi Formation has been sampled (C18r; ~41–40 Ma). Accordingly, here we use the paleomagnetic results of that continental sequence for the evaluation of the vertical-axis rotations. The ~41 to ~27 Ma deposits are characterized by red siltstones to medium sandstones with cross stratifications and incised channel fills

AGE (Ma)			FORMATION	THICKNESS	LITHOLOGY
0			Xiyu	200 - 2000 m	gray conglomerates
5		Pliocene	Artushi	200 - 3400 m	reddish-gray conglomerates and sandstones
10		Late	Pakabulake	350 - 2200 m	brownish-red to grayish-white mudstones and siltstones
15		Miocene	Anjuan	70 - 1000 m	brownish-red mudstones interbedded with grayish-green mudstones, siltstones and sandstones
20		Early			
25		Wuqia Group			
30		Late	Kezilouyi	200 - 500 m	red-beds including mudstones, siltstones, sandstones and gypsum interbeds
35		Early			
40		Middle	Wulagen	10 - 200 m	grayish-green mudstones intercalated with shell beds, shelly limestones and muddy siltstones (occasionally overlain by massive gypsum beds)
45		Eocene	Kalatar	20 - 180 m	grey massive limestones, marls and grayish-green mudstones with interbeds of shelly limestones, oolitic limestones, shell beds and gypsum
50		Early	Upper Qimugen		brownish-red (gypsiferous) mudstones intercalated with grayish-green mudstones (occasionally overlain by brown gypsiferous mudstones and massive gypsum beds)
55		Late	Lower Qimugen	10 - 150 m	grayish green mudstones, siltstones and fine-grained sandstones intercalated with shelly limestones
60		Paleocene	Aertashi	20 - 300 m	massive gypsum beds intercalated with gypsiferous mudstones and dolomitic limestones
65					

**Figure 2.** Generalized regional Cenozoic lithostratigraphy of the southwest Tarim Basin. The lithostratigraphy and corresponding thicknesses are summarized from *Jia et al.* [2004], *Mao and Norris* [1988], and *Tang et al.* [1989], whereas the preliminary age estimates are based upon calcareous nanofossils [Zhong, 1992], bivalves [Lan and Wei, 1995], ostracods [Yang et al., 1995], dinoflagellate cysts [Mao and Norris, 1988], benthic foraminifera [Hao and Zeng, 1984], and our previous integrated biomagnetostratigraphic study [Bosboom et al., 2013]. The shaded area shows the age range of the continental sediments analyzed in this study.

interbedded by (laminated, gypsiferous) mudstones and are interpreted as representing dominantly alluvial floodplain deposits with occasional (brackish) lacustrine intervals. Accumulation rates are relatively low and range from 5.6 to 23.2 cm/kyr [Bosboom et al., 2013]. The sampled strata are eastward from the eastern Pamir bounding faults and are essentially undisturbed with homoclinal ~15° northeastward dip at Kezi and ~40–65° eastward dip at Aertashi, in line with the trend of regional structures along the eastern Pamir.

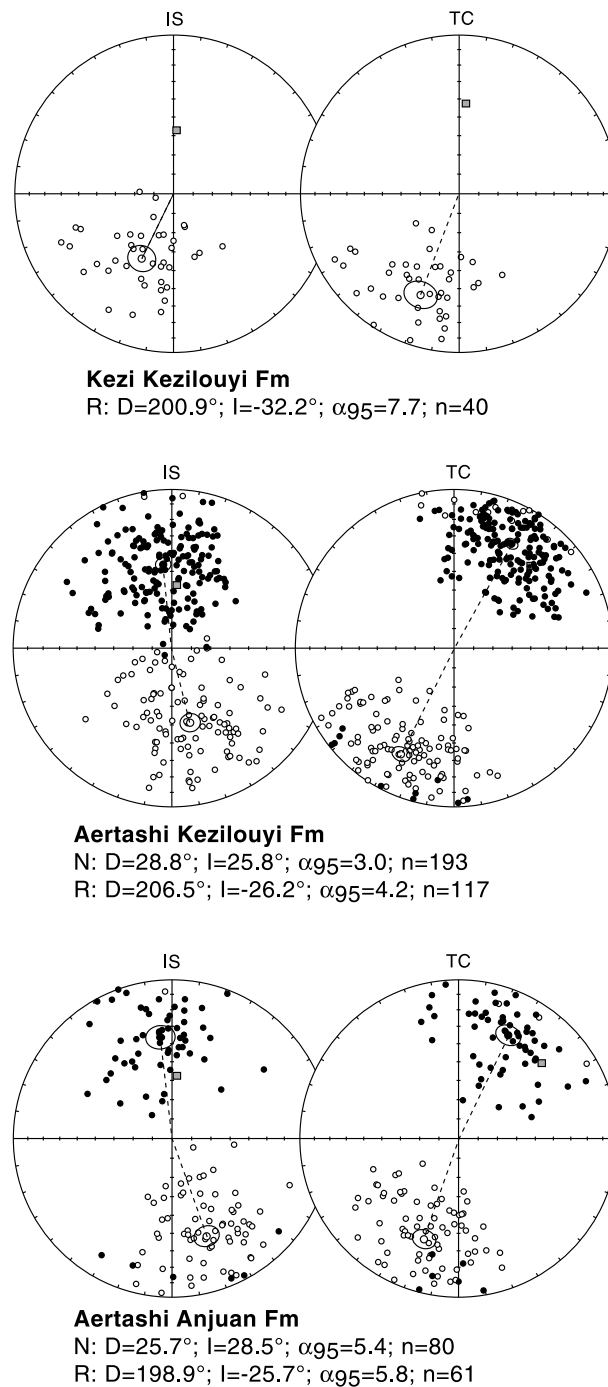
Previous paleomagnetic analyses have been carried out in the shielded Paleomagnetic Laboratory “Fort Hoofddijk” of the Faculty of Geosciences at the Utrecht University [Bosboom et al., 2013]. Here we use the data of all earlier-analyzed continental samples of the Wuqia Group from both the Kezi (43 samples dated ~41–40 Ma) and Aertashi sections (313 samples from the interval below the disconformity dated as ~41–36 Ma; 140 samples from the interval above dated as ~33–27 Ma) to calculate vertical-axis rotations.

### 3.1. Rock Magnetic Analyses

Based on previous temperature-dependent rock magnetic analyses (Curie balance and susceptibility bridge) on representative red bed samples [Bosboom et al., 2013], a decrease in magnetization is observed near the Curie temperature of magnetite (~580°C) and more frequently of hematite (~680°C). Previous measurement of the remanent magnetization after stepwise thermal demagnetization in shielded ovens indicates that after progressive removal of an overprint component at temperatures of 100 to 300°C, the characteristic remanent magnetization (ChRM) is composed of a low-temperature component (LTC) and a high-temperature component (HTC). These components are parallel, and both decay toward the origin. In general, the LTC is removed from 350 to 600°C, whereas the HTC is unblocked from 640 to 700°C, supporting the rock magnetic results that magnetite and hematite are the dominant ferromagnetic carriers. For more details on the rock magnetic analyses we refer to Bosboom et al. [2013].

### 3.2. ChRM Direction Analyses

The ChRM directions were calculated from orthogonal plots by application of principal component analysis [Kirschvink, 1980]. The line fits were performed on a minimum of four temperature steps. For our rotation analyses we have solely selected from the magnetostratigraphic data set the ChRM data of the highest quality, yielding



**Figure 3.** Equal-area plots of the ChRM directions, shown for each section and formation both for in situ (IS) versus tilt-corrected (TC) coordinates. Downward directions are shown as solid symbols, whereas upward directions are shown as open symbols. Fisher means are indicated for normal (N) and reversed (R) polarities with circles indicating the  $\alpha_{95}$  confidence limit. The direction of the present-day normal field is indicated by the grey square for comparison.

unambiguous directions and maximum angular deviations below  $15^\circ$  without forcing directions through the origin. After bedding-tilt correction, the selected directions group in two antipodal normal and reversed clusters on stereographic projections. Fisher statistics (Figure 3) [Fisher, 1953] were used to calculate the mean normal and reversed ChRM directions and their  $\alpha_{95}$  (95% confidence angle). The outliers and transitional directions positioned more than  $45^\circ$  from the normal and reversed means were iteratively rejected.



**Table 1.** Paleomagnetic Mean Directions From the Kezilouyi and Anjuan Formations at the Kezi and Aertashi Sections in the Southwest Tarim Basin<sup>a</sup>

Section (Age)	n	In Situ (IS)		Tilt Corrected (TC)		k	$\alpha_{95}$ (Deg)
		D (Deg)	I (Deg)	D (Deg)	I (Deg)		
Kezi (41–40 Ma) = normal	0						
Kezi (41–40 Ma) = reverse	17			203.9	216.9	11.3	11.1
Kezi (41–40 Ma) = all	17	26.9	54.2			11.9	10.8
Kezi (41–40 Ma) = all	17			23.9	36.9	11.3	11.1
Indeterminate reversals test							
Aertashi (41–36 Ma) = normal	95			32.4	26.8	15.4	3.8
Aertashi (41–36 Ma) = reverse	47			209.4	−31.5	10.7	6.7
Aertashi (41–36 Ma) = all	142	348.7	50.8			12.0	3.6
Aertashi (41–36 Ma) = all	142			31.2	28.3	13.0	3.4
Positive reversals test (classification B); critical angle = 8.0°; normal reverse angle = 5.4°.							
Aertashi (33–27 Ma) = normal	26			29.5	33.9	14.7	10.0
Aertashi (33–27 Ma) = reverse	16			204.3	−39.0	16.0	7.3
Aertashi (33–27 Ma) = all	42	341.2	40.6			15.0	5.9
Aertashi (33–27 Ma) = all	42			26.3	37.2	15.5	5.8
Positive reversals test (classification B); critical angle = 12.1°; normal reverse angle = 6.6°.							

<sup>a</sup>Note:  $n$  = number of sample characteristic remanent magnetization (ChRM) directions averaged to calculate site mean direction;  $D$  = declination and  $I$  = inclination of site mean directions for in situ (geographic) and tilt-corrected (stratigraphic) coordinates;  $k$  = concentration parameter;  $\alpha_{95}$  = angular radius of 95% confidence on mean direction. Averages of site mean directions are given by formation and by polarity (normal and reverse). Reliability is evaluated by the outcome of the reversals test of *McFadden and McElhinny* [1990].

For the Aertashi section, the data was separated into two age bins of ~41–36 Ma and ~33–27 Ma, respectively, below and above the observed disconformity.

### 3.3. Reliability Tests

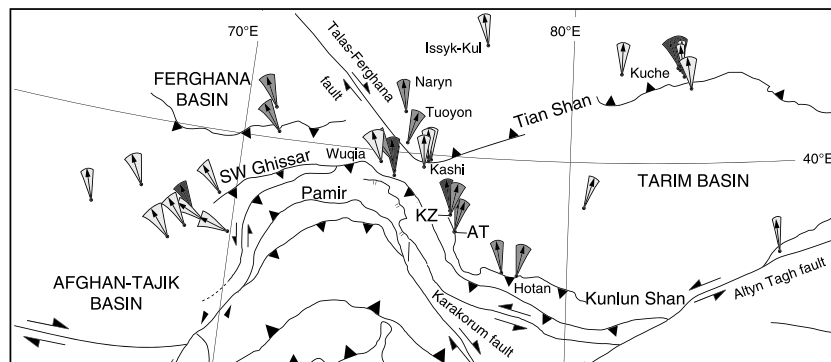
The uniform bedding orientation at both sections precludes a fold test, but to assess the nature of the acquired ChRM directions the reversals test of *McFadden and McElhinny* [1990] was applied. The two age bins of the Aertashi section both pass with classification B. This indicates a primary magnetization without secondary bias in directions, thus providing reliable results for rotational analysis. As the red beds of the Kezi section have solely yielded reversed ChRM directions, a reversal test cannot be applied. However, a primary origin is likely based on the consistency in the rock magnetic properties and ChRM directions in comparison to the Aertashi samples and because the ChRM directions in geographic coordinate depart significantly from the present-day field orientation.

## 4. Results

### 4.1. Rotational Analyses

To evaluate the direction and magnitude of vertical-axis rotations, we compare our well-dated locality-mean directions to expected directions derived at the locality sites from the Eurasian apparent polar wander path (APWP) of according age from *Torsvik et al.* [2008]. Rotations and flattening have been calculated according to methods of *Butler* [1992]. The mean inclination values are systematically lower than the  $59.0 \pm 2.5^\circ$  expected from the Paleogene Eurasian APWP, yielding  $21.5 \pm 5.1^\circ$  to  $30.7 \pm 3.4^\circ$  of flattening. This can be interpreted as resulting from inclination shallowing during depositional and compaction processes as observed in numerous red beds in Asia [e.g., *Dupont-Nivet et al.*, 2002b; *Gilder et al.*, 2001].

Observed declinations consistently yield clockwise rotations with respect to expected declinations at both sections (Table 1):  $21.6 \pm 4.2^\circ$  in 41 to 36 Ma strata then  $17.1 \pm 6.5^\circ$  in 33 to 27 Ma strata at the Aertashi section and  $14.2 \pm 11.5^\circ$  in 41 to 40 Ma strata at the Kezi section. These results are statistically indistinguishable given the confidence intervals such that it is not possible to infer if the rotation occurred gradually between 41 and 36 Ma; however, we can infer that most of it occurred after 36 Ma. To better understand the tectonic significance of these rotations and their evolution in time and space, they are discussed below in light of a regional review of previous paleomagnetic results



**Figure 4.** Simplified structural map of the Pamir collision zone (modified from Cowgill [2010]) showing the distribution of paleomagnetic rotations from Cretaceous and Cenozoic strata around the Pamir in Central Asia. Rotations and uncertainties are shown with respect to the Eurasian APWP (see Table 2 for complete list and references). Dark grey indicates Cretaceous data, medium grey indicates Paleogene data, and light grey indicates Neogene data. The results of this study are at the Aertashi (AT) and Kezi (KZ) sections.

#### 4.2. Comparison With Previous Paleomagnetic Results Around the Pamir

At the Aertashi section, previous results [Rumelhart *et al.*, 1999; Yin *et al.*, 2000] indicate low amounts ( $8.4 \pm 5.8^\circ$ ) of clockwise rotation from strata sampled stratigraphically above our own sampling and therefore necessarily younger. According to magnetostratigraphic dating of Yin *et al.* [2002], these rocks have been deposited between ~33 and ~24 Ma implying limited Neogene rotation. Together with our results showing significant clockwise rotations recorded in 41–36 Ma sediments, this suggests that the tectonic mechanism responsible for most of the rotation acquired at the Aertashi section occurred in Oligocene times before ~24 Ma.

To understand whether this rotation is only local or systematically extends regionally we review other results from Cretaceous and younger strata along the eastern Pamir and more generally in the Tarim Basin (Figure 4 and Table 2). Our slightly lower  $14.2 \pm 11.5^\circ$  rotation in 41 to 40 Ma strata observed at the Kezi section to the north suggests that clockwise rotations occurred systematically along the West Kunlun Shan with varying degrees of magnitude. However, previous contrasting results have been reported from Cretaceous to Paleogene continental and marine strata at the Yingjisha section only a few kilometers to the north of the Kezi section (Figure 4) [Chen *et al.*, 1992]. At this locality, mean declinations are low and yield no significant rotations when compared to the Eurasian APWP. However, the following evidence suggests that this site may be discarded for inferring a regional tectonic mechanism. This result has been previously associated with local structures departing from the regional trend [Yin *et al.*, 2000]. In addition, the absence of rotation in this site may also relate to the wholesale and regional remagnetization of the marine strata evidenced previously [Bosboom *et al.*, 2013] that would partially bias those data sets. Similarly, Li *et al.* [2013] recently reported results from a section referred to as the Qimugen section which is the same as the Kezi section reported here. These results are mostly marine sediments from the Kashi Group (i.e., from the levels –300 to 250 m in Li *et al.*, 2013) that have been shown to be biased by remagnetization [Bosboom *et al.*, 2013] yielding erroneously limited amounts of rotation and therefore should be rejected for tectonic analysis. Note that the stratigraphic divisions and the ages reported in Li *et al.* [2013] must be corrected according to the magnetostratigraphic constraints now available in Bosboom *et al.* [2013]. Accordingly, marine sediment reported by Li *et al.* [2013] from the Kashi Group includes the Qimugen, Kalatar, and Wulagen Formations (but not the Bashibulake Formation, which is not present in this part of the basin). Li *et al.* [2013] also report a few paleomagnetic results from the overlying continental red beds of the Wugua Group. Unfortunately, these results did not yield an interpretable set of directions, and the stratigraphic position of these rocks is not clear such that it is not possible to compare them with our results. In summary, after discarding results likely biased by remagnetizations [Chen *et al.*, 1992; Li *et al.*, 2013], paleomagnetic studies from the eastern flank of the Pamir indicate systematic clockwise rotations with maximum ~25° magnitude.

By comparison to previous results across the Tarim Basin, it is immediately apparent that these clockwise rotations do not continue systematically into the Tarim Basin. Both senses of rotations are observed in the



**Table 2.** Review of Paleomagnetic Results From the Tarim Basin Shown for Various Subregions<sup>a</sup>

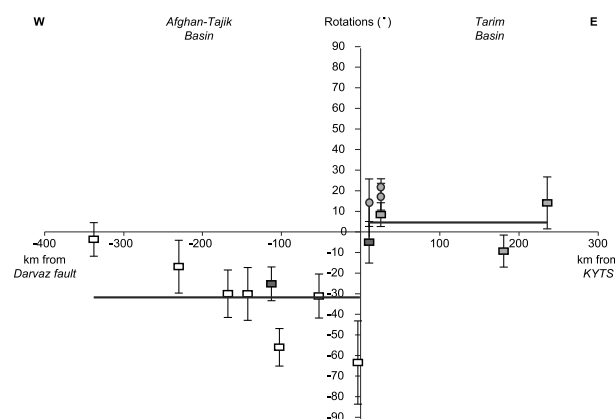
				Site		Observed Direction (TC)						Reference Pole				Rotation		
				Age	Ref.							Location	Age	Lat.	Long.	$\alpha_{95}$	$R$	$\pm$
Section	Formation	(Ma)		Lat. (°N)	Long. (°E)	$D$ (Deg)	$I$ (Deg)	$\alpha_{95}$ (Deg)	$n$		Test $\pm$	Age	Lat. (°N)	Long. (°E)	$\alpha_{95}$ (Deg)	$R$ (Deg)	$\pm$	$\Delta R$ (Deg)
Eastern Pamir																		
Aertashi	Wuqia Group	<33–24? Ma	1	38.1	76.4	17.6	36.9	5.0	56	s	+f C	30	82.7	152.5	2.8	8.4	$\pm$	5.8
Aertashi	Wuqia Group	33–27 Ma	*	38.0	76.6	26.3	37.2	5.8	42	s	A	30	82.7	152.5	2.8	17.1	$\pm$	6.5
Aertashi	Wuqia Group	41–36 Ma	*	38.0	76.6	31.2	28.3	3.4	142	s	A	40	82.3	150.5	2.8	21.6	$\pm$	4.2
Kezi	Wuqia Group	41–40 Ma	*	38.4	76.4	23.9	36.9	11.1	17	s	n/a	40	82.3	150.5	2.8	14.2	$\pm$	11.5
Yingjisha	Yingjisha-Kezilesu	K	2	38.5	76.4	9.6	38.4	8.0	9	S	n/a	100	78.5	179.7	2.7	−4.1	$\pm$	8.6
Altyn Tagh																		
Jianglisai		N1	1	38.0	86.5	−1.6	39.6	6.7	28	s	+f C	20	85.0	137.4	3.0	−6.7	$\pm$	7.7
Kuche Basin (Tian Shan)																		
Yaha	Kuche-Xiyu	5.3–1.7	3	41.9	83.3	−2.4	54.1	2.4	256	s	A	0	87.6	133.6	3.0	−4.9	$\pm$	4.7
Yaha	Jidike-Xiyu	12.6–5.2	4	41.9	83.3	−6.8	43.5	2.6	406	s	+f-r	10	87.2	125.0	2.5	−9.4	$\pm$	4.0
Section A	Jidike-Kuche	16.5–5.7	5	42.0	83.3	−2.3	46.1	2.1	66	S	+f A	10	87.2	125.0	2.5	−4.9	$\pm$	3.7
Section B	Kumugeliemu-Jidike	29.0–15.5	5	42.0	83.3	6.0	42.8	6.2	15	S	+f C	20	85.0	137.4	3.0	0.3	$\pm$	7.6
Kuche Basin	Suweiyi	$\pm$ N1	6	41.6	83.5	24.6	54.6	10.3	2	S	+f +r	50	79.1	154.2	2.6	10.2	$\pm$	14.7
Kuche Basin	Suweiyi	$\pm$ E3	6	41.6	83.5	2.2	45.3	13.8	3	S	+f +r	50	79.1	154.2	2.6	−12.2	$\pm$	16.1
Kuche Basin	Kumugeliemu	$\pm$ E1–2	6	41.6	83.5	−8.5	39.0	8.9	10	S	+f +r	50	80.9	162.0	2.6	−20.7	$\pm$	9.6
Kuche River	Qigu-Kumugeliemu	K	7	42.1	83.1	13.8	39.3	3.8	149	s	+f +r	100	78.5	179.7	2.7	−1.1	$\pm$	4.8
Kuche River-Bestantuogela	Kapusaliang Group	K	8	42.1	83.2	16.4	29.3	9.5	21	S	+f C	100	78.5	179.7	2.7	1.5	$\pm$	9.2
Kuche Basin	Bashenjiqike	K2	9	42.0	81.6	16.0	39.0	9.0	4	S	+f	75	79.9	171.7	1.5	2.5	$\pm$	9.4
Kezilenuer Channel	Bashenjiqike-Kumugeliemu	K1	7	42.1	83.1	−7.1	60.2	15.1	42	s	n/a	70	80.3	181.8	2.7	−19.6	$\pm$	25.4
Paicheng	Yageliemu-Kelaza	J3–K1	9	42.0	81.6	22.0	42.0	9.0	6	S	+f	130	75.7	167.7	6.4	2.8	$\pm$	11.9
Kashi Basin (Tian Shan)																		
Ganghangou	Atushi-Xiyu	2.2–1.0	10	39.8	76.2	15.9	32.5	10.6	33	s	C	0	87.6	133.6	3.0	13.2	$\pm$	10.6
Boguzihe	Atushi-Xiyu	3.6–1.4	10	39.8	76.2	−10.6	43.2	1.9	258	s	A	0	87.6	133.6	3.0	−13.3	$\pm$	3.8
North Kashi	Atushi	N2	11	39.6	76.0	−4.3	40.2	9.0	13	S	+f	0	87.6	133.6	3.0	−7.0	$\pm$	10.0
North Atushi	Atushi	N2	11	39.8	76.1	−13.1	45.1	7.2	11	S	+f	0	87.6	133.6	3.0	−15.8	$\pm$	8.8
North Atushi	Kezilouyi-Pakabulake	N1	11	39.8	76.1	−16.7	44.6	9.6	10	S	+f	10	87.2	125.0	2.5	−19.5	$\pm$	11.2
Tuoyon Basin (Tian Shan)																		
Locality A + B	Upper Basalt Series	E1v	12	40.2	75.3	48.4	49.1	6.6	20	S	+f	60	79.0	166.8	2.4	34.2	$\pm$	8.5
Tuoyon	Kezilesu Group	K1	13	40.2	75.3	37.9	38.6	6.8	5	S	+f	125	76.3	175.6	6.2	21.1	$\pm$	9.3
Tuoyon	Kezilesu Group	K1v	13	40.2	75.3	31.9	49.9	10.6	13	S	+f	125	76.3	175.6	6.2	15.1	$\pm$	14.6
Wuqia area																		
East Kulukeqiati	Atushi	N2	11	39.8	74.6	−14.8	50.6	24.3	5	S	+f	0	87.6	133.6	3.0	−17.5	$\pm$	32.5
East Kulukeqiati	Kezilouyi-Pakabulake	N1	11	39.8	74.6	−11.9	42.0	7.8	15	S	+f	10	87.2	125.0	2.5	−14.8	$\pm$	8.8
West Wuqia	Kashi Group	E2	11	39.8	74.7	−23.1	47.4	11.1	8	S		40	82.3	150.5	2.8	−33.1	$\pm$	13.6
Wuqia area	Yingjisha-Kezilesu	K	2	39.5	75.0	10.3	38.6	8.2	18	S	+f	100	78.5	179.7	2.7	−3.4	$\pm$	8.8
Central Tarim and Hotan Basin																		
Maza Tagh	Wuqia Group	N1	14	38.5	80.5	24.7	29.4	6.2	30	S	+f	20	85.0	137.4	3.0	19.1	$\pm$	6.5
Puska	Kashi Broup	E2	1	37.1	78.4	4.3	24.3	8.4	22	s	+f Cr	50	79.1	154.2	2.6	−9.3	$\pm$	7.8
Duwa-Piyaleman	Aertashi-Qimugen	E1	15	37.0	79.0	27.8	30.0	13.3	5	S	+f	60	79.0	166.8	2.4	14.1	$\pm$	12.6

# Notes to Table 2:

<sup>a</sup>Age of sampled formation given by numbers when magnetostratigraphic control on age span is available or given by epoch notation otherwise (K1 = Early Cretaceous; K2 = Late Cretaceous; E1 = Paleocene; E2 = Eocene; E3 = Oligocene; N1 = Miocene; N2 = Pliocene; v = data from volcanic rocks;  $\pm$  = age estimated). Lat. = latitude and Long. = longitude of section location;  $D$  = declination and  $I$  = inclination for tilt-corrected (stratigraphic coordinates);  $\alpha_{95}$  = angular radius of 95% confidence on mean direction;  $n$  = number of sites (S) or samples (s) used to calculate mean directions; Test refers to the outcome of reversals ( $r$ ) or fold test ( $f$ ) as positive (+), negative (−), not applicable (n/a), or the classification (A, B, or C) of the reversals test of *McFadden and McElhinny* [1990]. Reference poles are the Eurasian paleomagnetic poles from *Torsvik et al.* [2008]. Shaded reference pole data indicate that mean poles have been calculated for long age spans of more than 30 Myr.  $R$  = vertical-axis rotation (clockwise is positive) and  $\Delta R$  = 95% confidence limit on rotation. References (Ref.): \* = this study; 1, *Rumelhart et al.* [1999]; 2, *Chen et al.* [1992]; 3, *Huang et al.* [2010]; 4, *Charreau et al.* [2006]; 5, *Huang et al.* [2006]; 6, *Fang et al.* [1998]; 7, *Peng et al.* [2006]; 8, *Tan et al.* [2003]; 9, *Li et al.* [1988]; 10, *Chen et al.* [2002]; 11, *Huang et al.* [2009]; 12, *Huang et al.* [2005]; 13, *Gilder et al.* [2003]; 14, *Dupont-Nivet et al.* [2002a]; 15, *Gilder et al.* [1996].

Hotan Basin along the West Kunlun Shan (Puska and Duwa sections) and in central Tarim (Maza Tagh section) that have been attributed equally to either wholesale Tarim block rotation or recent local structures [Dupont-Nivet et al., 2002a; Gilder et al., 1996; Rumelhart et al., 1999; Yin et al., 2000]. Along the left-lateral Altyn Tagh fault little to no rotations are observed locally and regionally [Dupont-Nivet et al., 2002b, 2003; Dupont-Nivet et al., 2004; Rumelhart et al., 1999; Yin et al., 2000]. Along the southern Tian Shan from the Wuqia area to the Kashi and Kuche Basins further east, rotations are predominantly counterclockwise or insignificant and have been associated with Neogene left-lateral transpressive shear along the Tian Shan range itself [Charreau et al., 2006; Chen et al., 2002, 1992; Fang et al., 1998; Huang et al., 2009, 2010; Li et al., 1988; Peng et al., 2006; Tan et al., 2003]. Departing from this general trend are clockwise rotations reported from Cretaceous-Paleocene volcanic rocks in the Tuoyun Basin associated with the right-lateral Talas-Ferghana fault [Gilder et al., 2003; Huang et al., 2005]. In summary, clockwise rotations observed along the eastern Pamir limb do not extend systematically and regionally into the Tarim Basin, where Cenozoic rotations are generally low and associated with local structures (Figure 5).

On the western side of the Pamir salient (Figure 4 and Table 3), Cretaceous to Cenozoic results are strikingly different with systematic counterclockwise rotations extending widely throughout the Afghan-Tajik and Ferghana Basins [Bazhenov and Mikolaichuk, 2002; Bazhenov et al., 1994; Burtman, 2000; Pozzi and Feinberg, 1991; Thomas et al., 1993, 1994]. These rotations show a clear westward decreasing trend ranging from  $\sim -60^\circ$  along the Darvaz fault on the eastern Pamir limb to no significant rotation over  $\sim 300$  km to the west (Figure 5). Structural and kinematic reconstructions show that this trend can be reconciled by the relative displacement and rotation of finite crustal thrust sheets in response to the regional left-lateral shear related to the northward Pamir indentation [Bourgeois et al., 1997; Thomas et al., 1994].



**Figure 5.** Vertical-axis rotations plotted against approximate east-west distance from the Kashgar-Yecheng transfer system (KYTS) marking the eastern margin of the Pamir and the Darvaz fault marking its western margin. Solid lines indicate the mean observed rotation on either side of the Pamir, showing that the average varies from  $-32.2^\circ$  anticlockwise rotation in the Afghan-Tajik Basin on the western side to  $6.5^\circ$  clockwise rotation in the Tarim Basin on the eastern side. As in Figure 5 dark grey indicates Cretaceous data, medium grey indicates Paleogene data, and light grey indicates Neogene data. The results of this study are shown by circles (instead of squares).

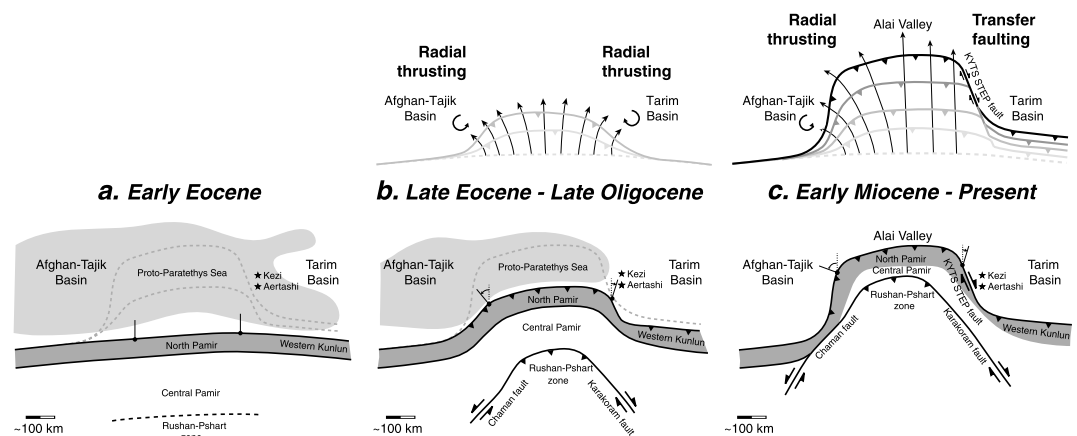
In summary, tectonic rotations around the Pamir show a strong asymmetry between regionally extensive systematic counterclockwise rotation in Cretaceous to Neogene strata on the western side of the Pamir contrasting with Oligocene clockwise rotations concentrated along the eastern Pamir limb that do not extend far eastward into the Tarim Basin (Figures 4 and 5).

## 5. Discussion

The curved geometry of the Pamir has been related to end-member models: (1) rotation by oroclinal bending or radial thrusting of the Pamir arc [Bazhenov and Burtman, 1986; Bazhenov et al., 1994; Robinson et al., 2004; Strecker et al., 1995] or (2) transfer faulting induced by opposite shear along the

**Table 3.** Review of Paleomagnetic Results From Tajikistan and Kyrgyzstan Shown for Various Basins<sup>a</sup>

	Age	Ref.	Site Location		Observed Direction (TC)						Reference Pole				Rotation		
Section	(Ma)		Lat. (°N)	Long. (°E)	D (Deg)	I (Deg)	$\alpha_{95}$ (Deg)	n	Test ±	Age	Lat. (°N)	Long. (°E)	$\alpha_{95}$ (Deg)	R (Deg)	±	$\Delta R$ (Deg)	
Afghan-Tajik Basin (Tajikistan)																	
Kalinabad	N1	1	38.0	69.0	−50.0	33.0	9.0	13	L	n/a	20	85.0	137.4	3.0	−56.0	±	9.1
Aksu	N1	1	38.0	68.6	−24.0	33.0	13.0	5	L	n/a	20	85.0	137.4	3.0	−30.1	±	12.8
Pyryagata	N1	1	37.7	68.3	−24.0	30.0	12.0	6	L	+ (f)	20	85.0	137.4	3.0	−30.0	±	11.5
Pulkhakim	N1	1	39.1	67.5	−11.0	35.0	13.0	10	L	+ (f) + (r)	20	85.0	137.4	3.0	−17.2	±	13.1
Tukaynaron	E3-			N1	1	38.8	69.6								−25.0		30.0
L	+ (f) + (r)		11.0	10	20	85.0	137.4		3.0						−31.1	±	10.7
South Darvaz	E2-			N1	1	37.7	68.1								−56.0		32.0
21.0	3	L	+ (r)	25	84.1	147.1	2.8								−63.4	±	20.2
Nurek Dam + Nurek Pass + Gissar + Ragoon	K1	2	38.3	68.9	−9.5	55.4	4.0	53	s	+ (f)	125	76.3	175.6	6.2	−25.2	±	8.2
Aksay Basin (Kyrgyzstan)																	
Tekelik	E2-3	3			14.6	54.0	3.8	18	L	+ (f)	40	81.7	154.5	2.8	11.0	±	5.7
Chatkal Basin (Kyrgyzstan)																	
Chatkal	E	4	41.7	71.2	−8.0	42.0	9.0	10	L	n/a	40	82.3	150.5	2.8	−18.3	±	10.2
Ferghana Basin (Kyrgyzstan)																	
Tash-Kumyr + Ala- Buka + South Ferghana	E	4	41.1	71.2	−18.0	34.0	9.0	9	L	+ (f) + (r)	40	82.3	150.5	2.8	−28.2	±	9.2
Issyk-Kul Basin (Kyrgyzstan)																	
Dzhety- Ogyuz + Karakoo + Toru Aygyr	E2-			N1	4	42.4	77.1		2.0		49.0	6.0	13	L	+	(f) 2.8	
−7.8	±	+		(r)	8.0												
Naryn Basin (Kyrgyzstan)																	
Karabulan + Djaman- Davan + Makmal	E	4	41.2	74.7	5.0	37.0	11.0	16	L	+ (f) + (r)	40	82.3	150.5	2.8	−5.2	±	11.5

<sup>a</sup>See note of Table 2 for explanation. References: 1, Thomas et al. [1994]; 2, Pozzi and Feinberg [1991]; 3, Bazhenov and Mikolaichuk [2002]; 4, Thomas et al. [1993].


**Figure 6.** Proposed tectonic and paleogeographic evolution of the Pamir salient (modified after Cowgill [2010]), based upon results of this study and previous studies of the proto-Paratethys Sea [Bosboom, 2013; Burtman, 2000; Burtman et al., 1996; Coutand et al., 2002; Lan and Wei, 1995; Tang et al., 1989]. The paleogeographic evolution is shown in the lower graphs with the approximate paleogeographic extent of the sea shaded in light grey for the (a) Early Eocene and (b) before its final retreat in the Late Eocene. The upper graphs show the corresponding kinematic models. The Pamir evolved symmetrically with radial thrusting causing rotation on both sides until the Late Oligocene. In the Late Oligocene to Early Miocene, deformation became asymmetric with ceased clockwise rotation in the Tarim Basin and continued anticlockwise rotation on the western side in the Afghan-Tajik Basin. This change is attributed to the initiation of slip along the Kashgar-Yecheng transfer system (KYTS) along the eastern Pamir in response to slab tear of the underriding Alai plate. See the discussion for a complete overview of this proposed evolution.

eastern (sinistral) and western (dextral) margins of the Pamir [Burtman and Molnar, 1993; Searle, 1996]. A hybrid of the above-mentioned end-member models has been recently proposed by Cowgill [2010]. This hybrid model involves northwest directed radial thrusting on the Pamir's western flank and transpressional dextral slip transfer faulting along the Kashgar-Yecheng transfer system (KYTS) on its eastern flank. This model is supported by Li *et al.* [2013] albeit based on data biased by remagnetization, yielding erroneously no rotation of the eastern flank since Paleocene times. In contrast, our reliable results indicate a regional Oligocene clockwise rotation and suggest this rotation mostly ceased in Neogene times. Our results thus imply a two-stage evolution that can be reconciled by the following model (Figure 6). After the Early Eocene initiation of the Pamir indentation associated with the Indo-Asia collision, the deformation propagated from Late Eocene to Late Oligocene into a proto Tajik-Tarim foreland basin inducing symmetric rotations by radial thrusting on either side of the nascent Pamir salient. By Early Miocene time, the observed asymmetry in the pattern of rotations indicates that radial thrusting did not continue east of the Pamir as it did to the west but was replaced by a mechanism such as strike-slip transfer faulting with limited distributed shear.

This model is consistent in time with the recently dated paleogeographic evolution of the proto-Paratethys Sea (Figure 6), involving its stepwise westward retreat in the Eocene forced by short-term eustasy and long-term tectonism related to the Pamir indentation [Bosboom *et al.*, 2013, 2011; Bosboom, 2013]. In the Early Eocene marine deposits had their maximum extent reaching far eastward into the Tarim Basin [Burtman, 2000; Burtman *et al.*, 1996; Lan and Wei, 1995; Tang *et al.*, 1989]. The maximum extent of each of the next incursions reached successively less far into the Tarim Basin; the last one reaching only the westernmost Tarim Basin in Late Eocene times [Bosboom, 2013]. The complete disappearance of the sea from Central Asia is poorly constrained to the Oligocene, followed by mostly continental deposition in Late Oligocene and Early Miocene times [e.g., Burtman, 2000; Burtman *et al.*, 1996; Coutand *et al.*, 2002]. This suggests that the observed Oligocene rotations may be related to tectonism propagating northward after the Late Eocene regional sea retreat and disappearance. After the Oligocene, a major right-lateral strike-slip system is reported to start in the Early Miocene along the eastern Pamir [Sobel and Dumitru, 1997; Sobel *et al.*, 2011]. This is supported locally at Aertashi by the initiation of proximal coarse-grained clastic deposition from ~24 Ma [Yin *et al.*, 2002] interpreted as a response to the initial dextral slip between the Pamir and the Tarim Basin [Cowgill, 2010]. Neogene decoupling of the Pamir from Tarim along this major strike-slip system is corroborated by the limited rotations accumulated in the Neogene with no regional consistency east of the Pamir into the Tarim Basin. This probably also corresponds to an important geodynamic change consistent with Early Miocene ages of exhumation and deformation in the eastern Pamir, Western Kunlun Shan, and Tian Shan [e.g., De Grave *et al.*, 2012; Sobel and Dumitru, 1997; Sobel *et al.*, 2006].

Finally, our results are consistent in time and space with the recently proposed intracontinental subduction models of Pamir evolution [Negredo *et al.*, 2007; Sobel *et al.*, 2013]. In these models, Eocene break off of the north dipping Indian slab associated with the Indo-Asia collision is followed by a period of intense deformation related to subduction inversion and the initiation of a new intracontinental south dipping subduction at ~25 Ma [Negredo *et al.*, 2007]. This is in good agreement with the observed Oligocene rotations with radial thrusting on either side of the nascent Pamir salient. Sobel *et al.* [2011, 2013] further suggest that the Pamir indentation could have been driven by roll back of the south dipping slab starting at ~25 Ma with a curved slab on its western flank and the initiation of a slab tear (or STEP, Subduction-Transform Edge Propagator as defined by Govers and Wortel [2005]) along its eastern flank linked to the dextral KYTS (Figure 6). This is consistent with the observed asymmetric distribution rotations starting in Miocene times. On the western flank, regionally distributed counterclockwise rotations would have continued into the Miocene in response to the retreating curved slab. On the eastern flank, clockwise rotations would have stopped after the Oligocene when the STEP initiated yielding a strike-slip system with limited distributed shear.

## 6. Conclusions

Arc-shaped ranges may result from a wide array of potential tectonic mechanisms yielding characteristic patterns of vertical-axis rotations that can be quantified using paleomagnetism [Weil and Sussman, 2004]. The case of the Pamir range is particularly interesting because of the asymmetry in observed rotations on either side of the arc resulting from contrasting mechanisms but yielding a seemingly symmetric shape in map view. Another peculiar aspect, suggested here, is the shift of the rotational pattern from symmetric to

asymmetric in the Late Oligocene to Early Miocene that enables us to identify a major change in geodynamic regime. This shows generally that regular arcuate structures may in fact be the result of a protracted history and cannot be assumed to have evolved regularly since inception. The analysis of vertical-axis rotations using paleomagnetism provides a tool to quantify the evolution of arcuate belts in time that can be particularly useful to constrain geodynamic models of these structures [e.g., Schellart and Rawlinson, 2010].

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